High Brightness LPP Light Sources for High Volume Inspection

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Presentation Outline

- ALPS Program Overview
- ALPS II Performance
- Plasma Emission Characterization
- Debris Mitigation, Cleanliness and Source Optics
- Alternative Emission Windows
- Summary & Conclusions

EUV Source Technology at ETH Zurich

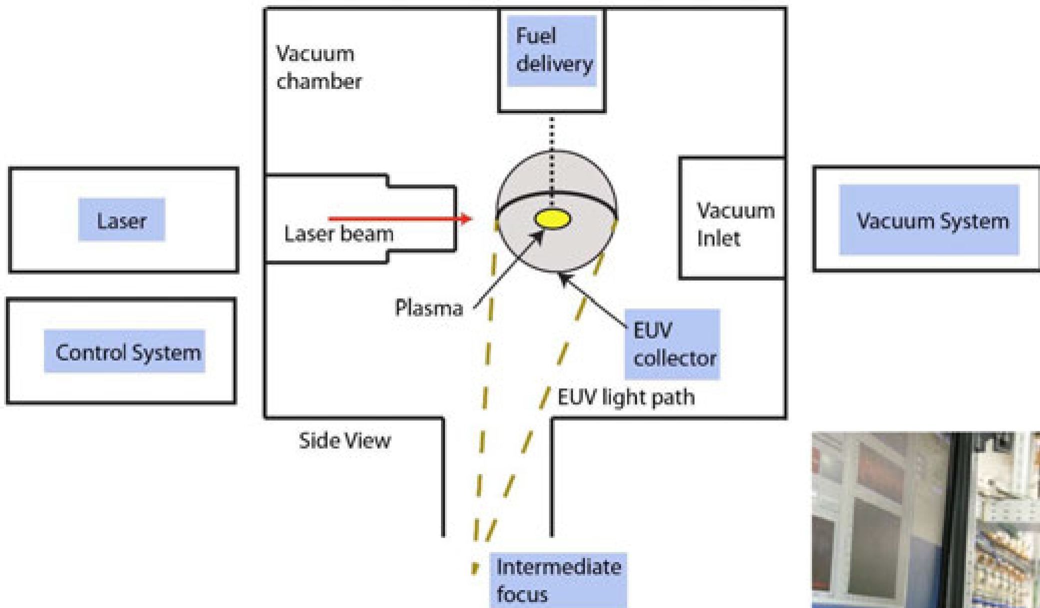
- Research & Development of **droplet-based LPP sources** since 2007
- Fully automated functioning system tested for 100's of hours of operation
- Main application in EUV photomask inspection, such as AIMS™, actinic blank and pattern inspection

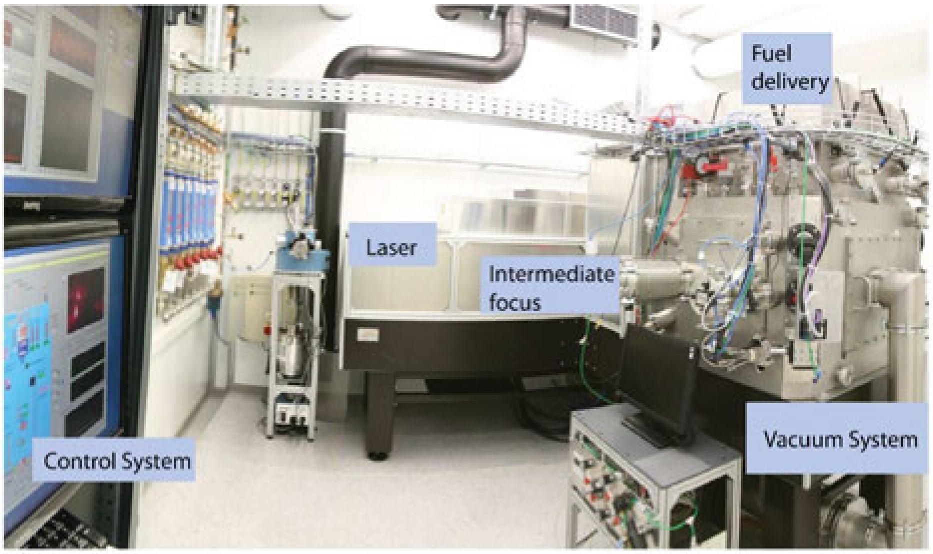
Recent System level advancements:

- Emission stability using droplet control in time and space	(-2013)
- Characterization of source emission and debris generation	(-2014)
- Debris mitigated EUV collector	(2014)
- Cleanliness validation of tin-based LPP source after IF	(2014)

- **Life-Time assessments for 24/7 operation in industrial environment, in accordance with industry requirements in terms of tool availability and cost-of-ownership**
- **Long-term effort towards other wavelengths (Watt range)**

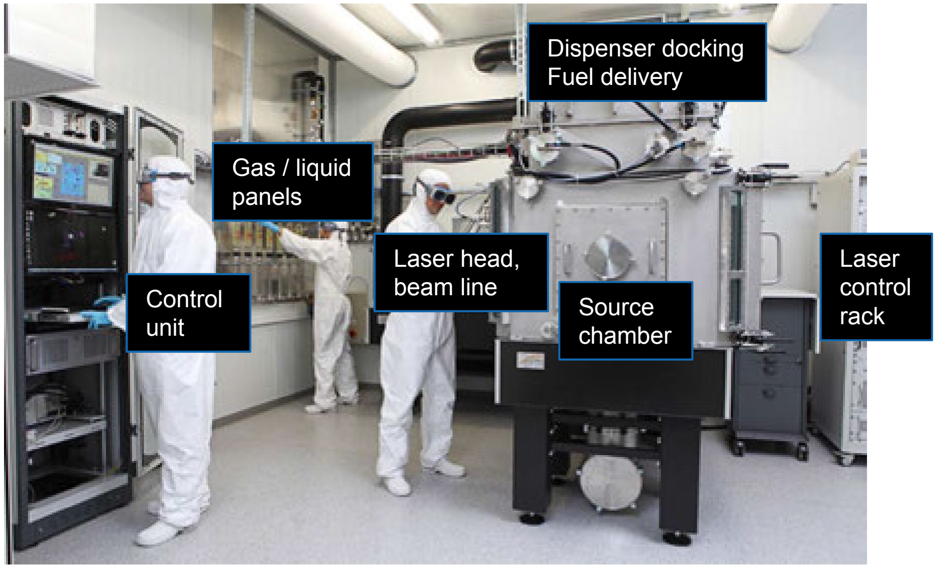
ALPS II Prototype Laser-produced Plasma Source for HVM application





www.lec.ethz.ch/plasma

ALPS II EUV Light Source – Key Numbers



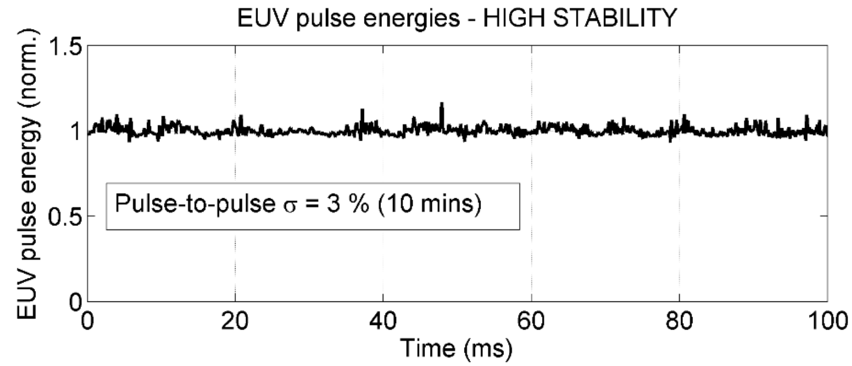
Parameters	Value
Laser power on target (W)	1600
Laser frequency (kHz)	>6
Laser focal spot size (µm)	70 (FWHM)
EUV source size (µm)	60 (FWHM)
Conversion efficiency (%)	>1%
Source power at the source (W)	>12
Source brightness (W/mm^{2}sr)	350

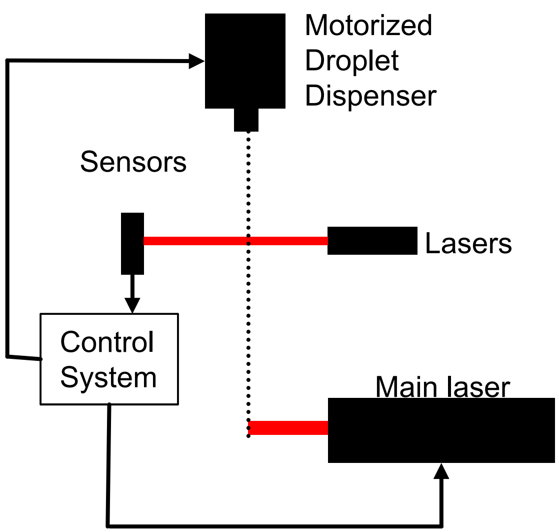
- Driven by DPSS Nd:YAG laser (average power of 1.6 kW, 1.064 µm, 6-20 kHz).
- 6th generation in-house droplet dispenser with >30 µm tin droplet generation for hours of operation.
- Droplet tracking system with laser triggering on individual droplets enables droplet-laser alignment within <10% of droplet diameter.
- Full diagnostic including in-band energy monitors and out-of-band spectroscopy
- Debris mitigated grazing incidence collector, including clean IF module with imaging capability.
- Compatible with various collector configurations

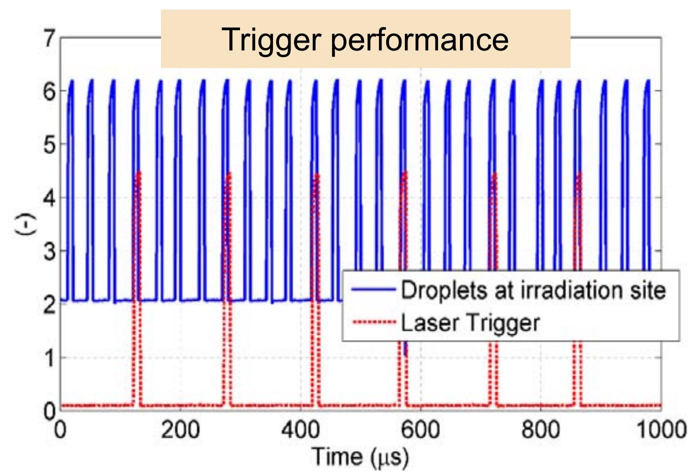
EUV Emission Stability

- Integrated EUV pulse energies for 10 mins source operation

- EUV energy monitor (ML, Zr filter) and gated hardware integrator. Source operated at 7 kHz repetition rate.



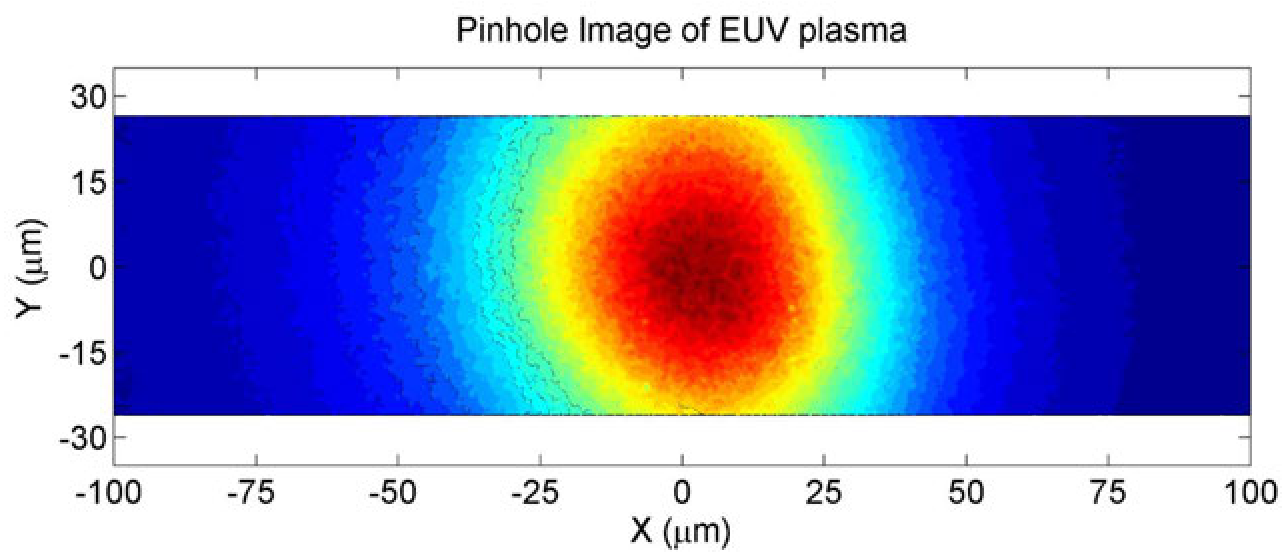




- **Pulse-to-pulse stability of EUV energy of 3% (σ)** has been achieved.
- Strong dependence between EUV pulse-to-pulse stability and trigger / droplet tracking performance

Source Size from Pinhole Camera Measurements

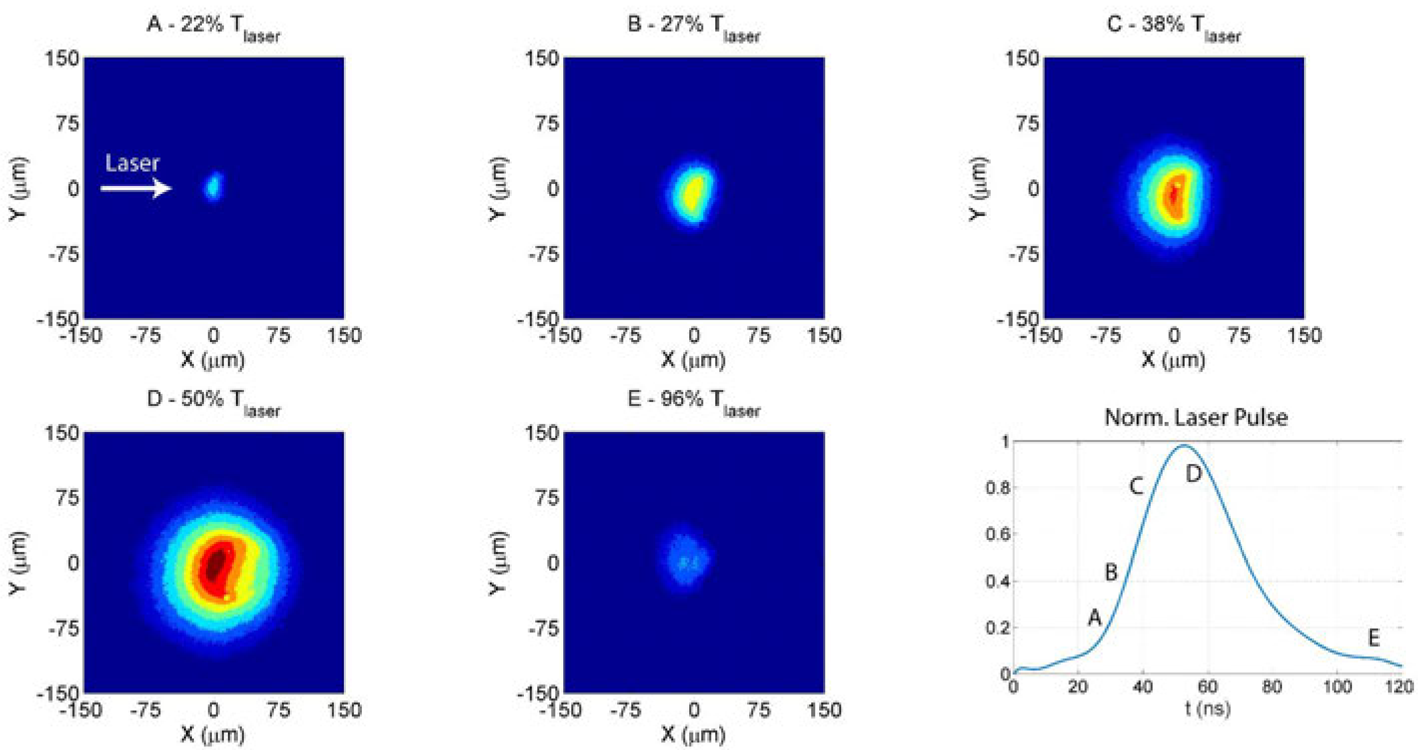
- EUV emission (Zr-filtered) recorded with an X-ray CCD pinhole camera, located at 20 mm from the plasma with an orifice size of 20 µm (magnification 40x).
- Exposure time of 140 ms for standard operating conditions (tin droplets, 200 GW/cm^2, camera at 90° from laser axis)



- The dimensions of the plasma in the direction of the laser axis and the direction of the train equal 60 µm and 70 µm, respectively.
- For a given etendue requirement, the source dimensions determine the collection angle, hence size of the source mirror.

Fast Nanosecond Imaging of Plasma (Visible)

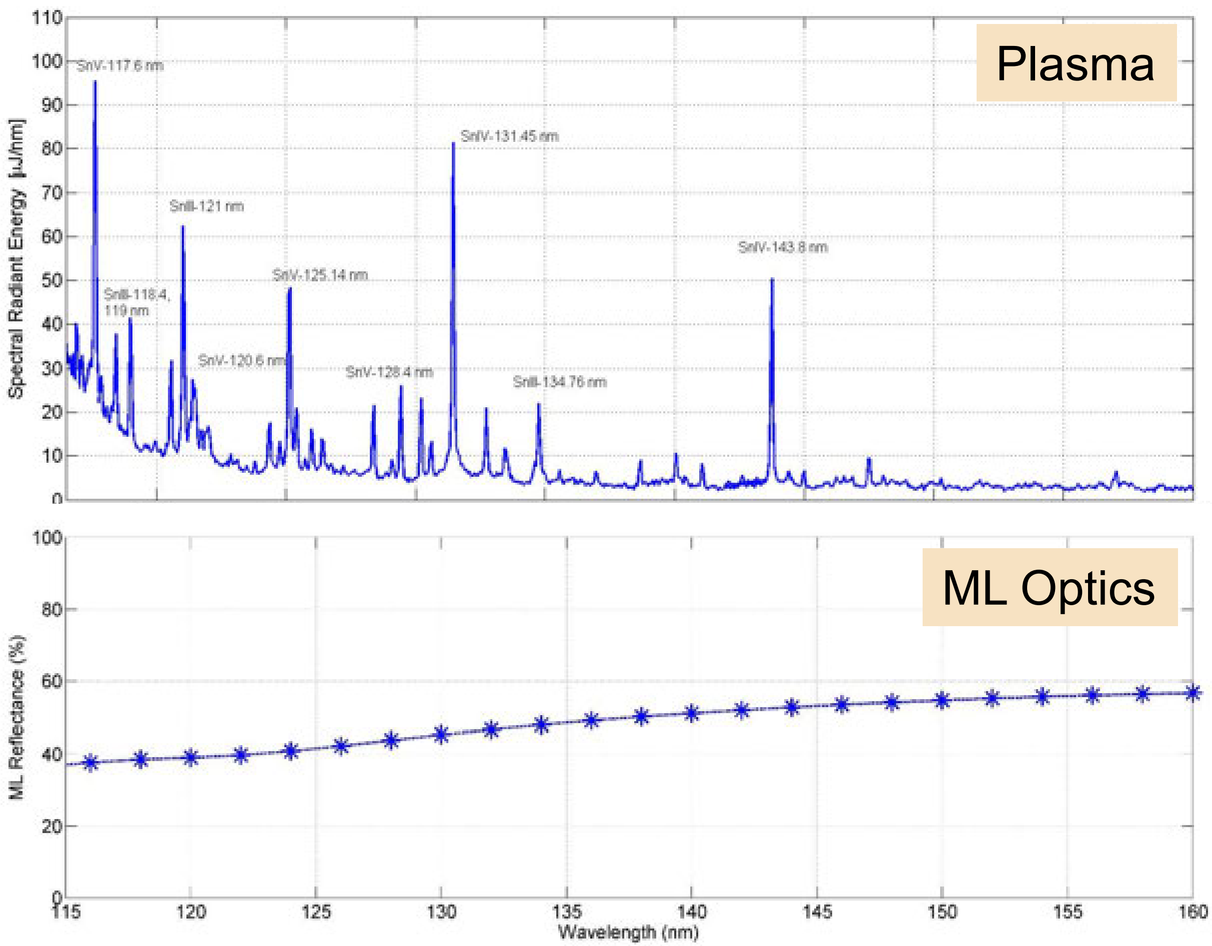
- Visible (400 – 700 nm) emission captured from a single plasma with an exposure time of 5 ns for standard operating conditions (tin droplets, 200 GW/cm^2, camera at 90° from laser axis)
- Resolution of single pulse dynamics (not captured by long exposure of pinhole camera)



- Peak emission obtained around peak laser intensity
- Emission is mainly Bremsstrahlung emission, as opposed to line emission from Sn and Sn$^+$, which appears at larger time scales.

VUV Spectroscopy for Out-of-Band Emission

- Spectrometer with holographic gratings (1200, 2400 Gr/mm) and back-illuminated CCD
- Measurements at 950 mm from plasma, at 60° from laser axis. Ar background at 0.1 mbar.



- From 115 nm to 160 nm the emission lines are related to atomic transitions of Sn III to Sn V.
- **Significant reflection of OOB tin emission expected from ML (into SPF)**

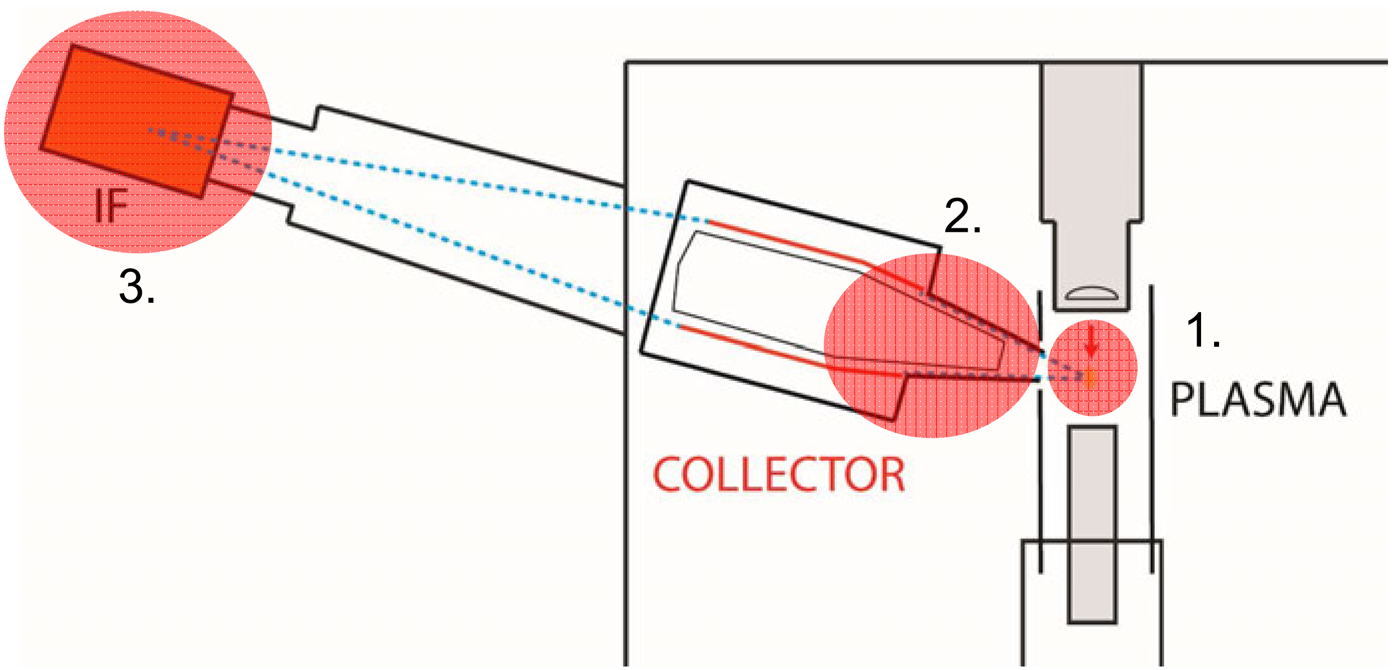
Source: optiX fab

Debris Mitigation Strategy

A. Limit debris formation

B. Mitigate debris

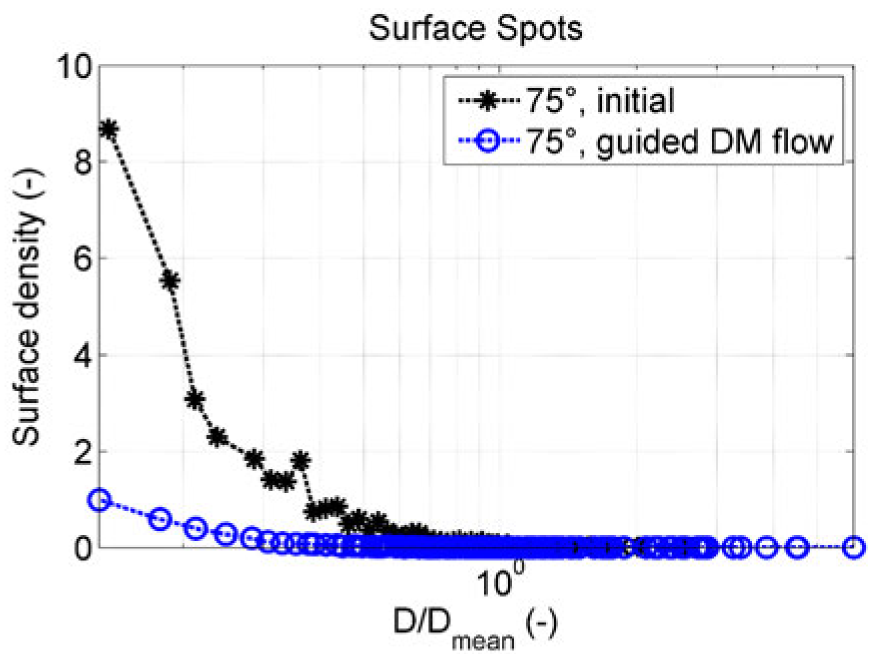
LAYER 1. Control debris around plasma
LAYER 2. Control debris in the collector module
LAYER 3. Control debris at IF

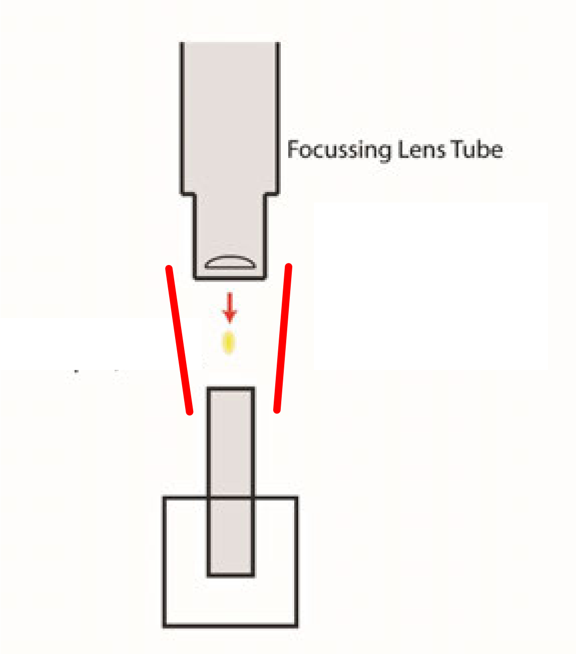


Efficient Debris Mitigation around Plasma Site

DM LAYER 1

- Optimized flow control and EUV transmission of debris mitigation gas around irradiation site
- Tin debris captured on Si witness plates

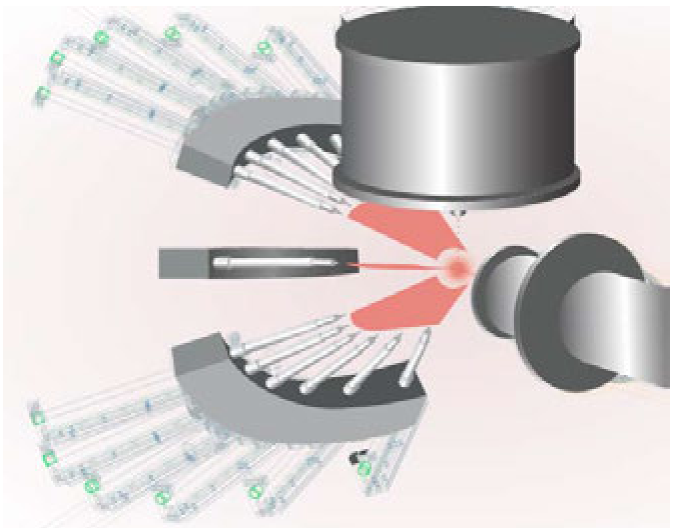


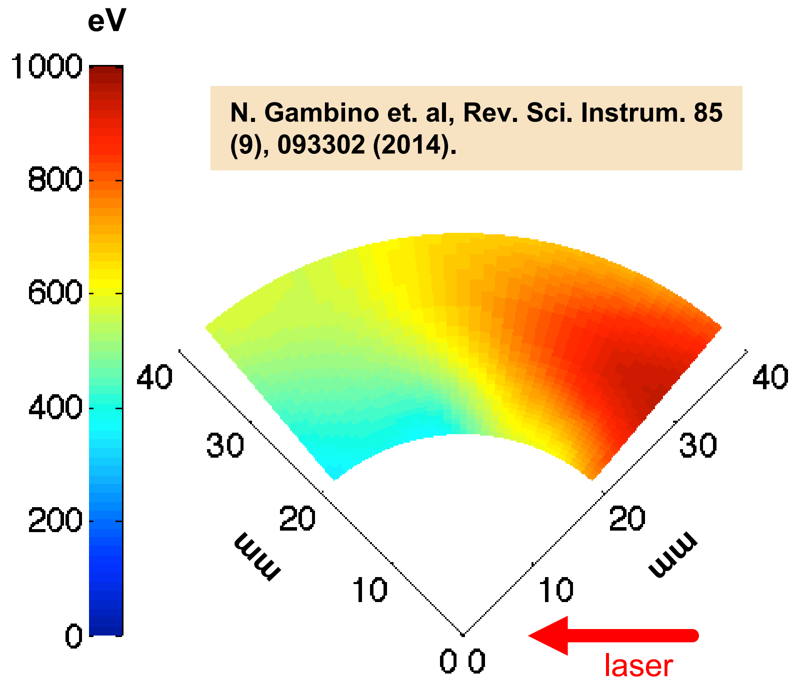


- Low energy debris is entrained by high momentum flow.
- Significant reduction (9x) of covered surface by efficiently tuning and guiding mitigation gases in the vicinity of the plasma. EUV emission is kept constant.

Ion Angular Distributions measured by Langmuir Probes

- Temporally resolve the angular and radial ion and electron distribution to yield a hemispherical mapping around the droplet.
- Kinetic energies are derived from time-of-flight measurements



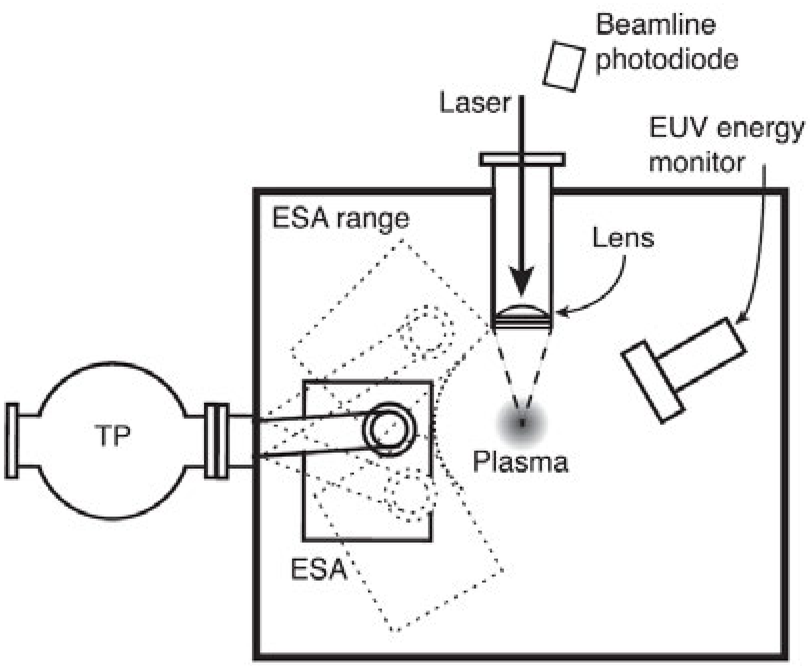


N. Gambino et. al, Rev. Sci. Instrum. 85 (9), 093302 (2014).

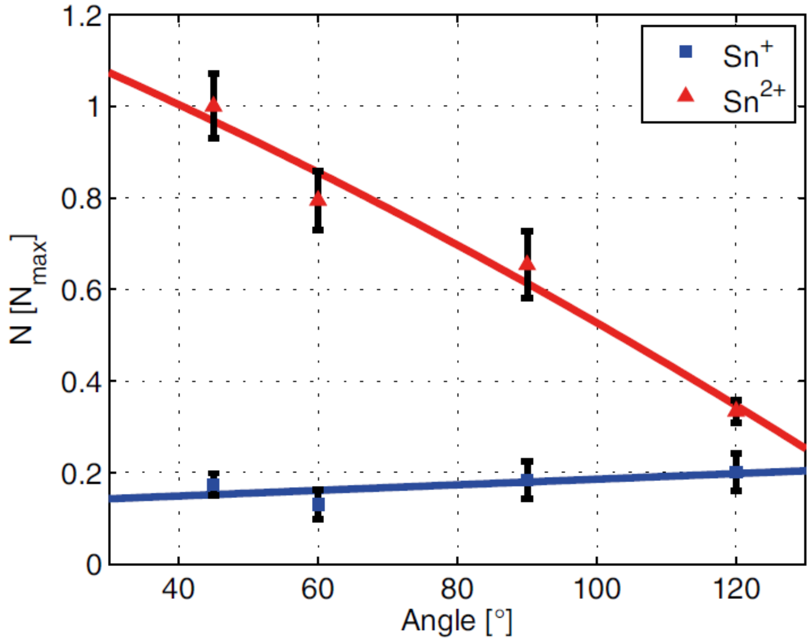
- Largest kinetic energies (damage potential) in forward direction
- Radial acceleration of ions (more pronounced on backside) at the considered length scales can be explained by self-induced electric field on the order of 30 MV/cm.

Ion Angular Distributions measured by Electrostatic Analyzer

- Electrostatic Analyzer (ESA) located at 150 mm from plasma at different angular positions. Different ion species can be resolved with information on abundance and kinetic energy.



A. Z. Giovannini et. al, J. Appl. Phys. 117, 033302 (2015).

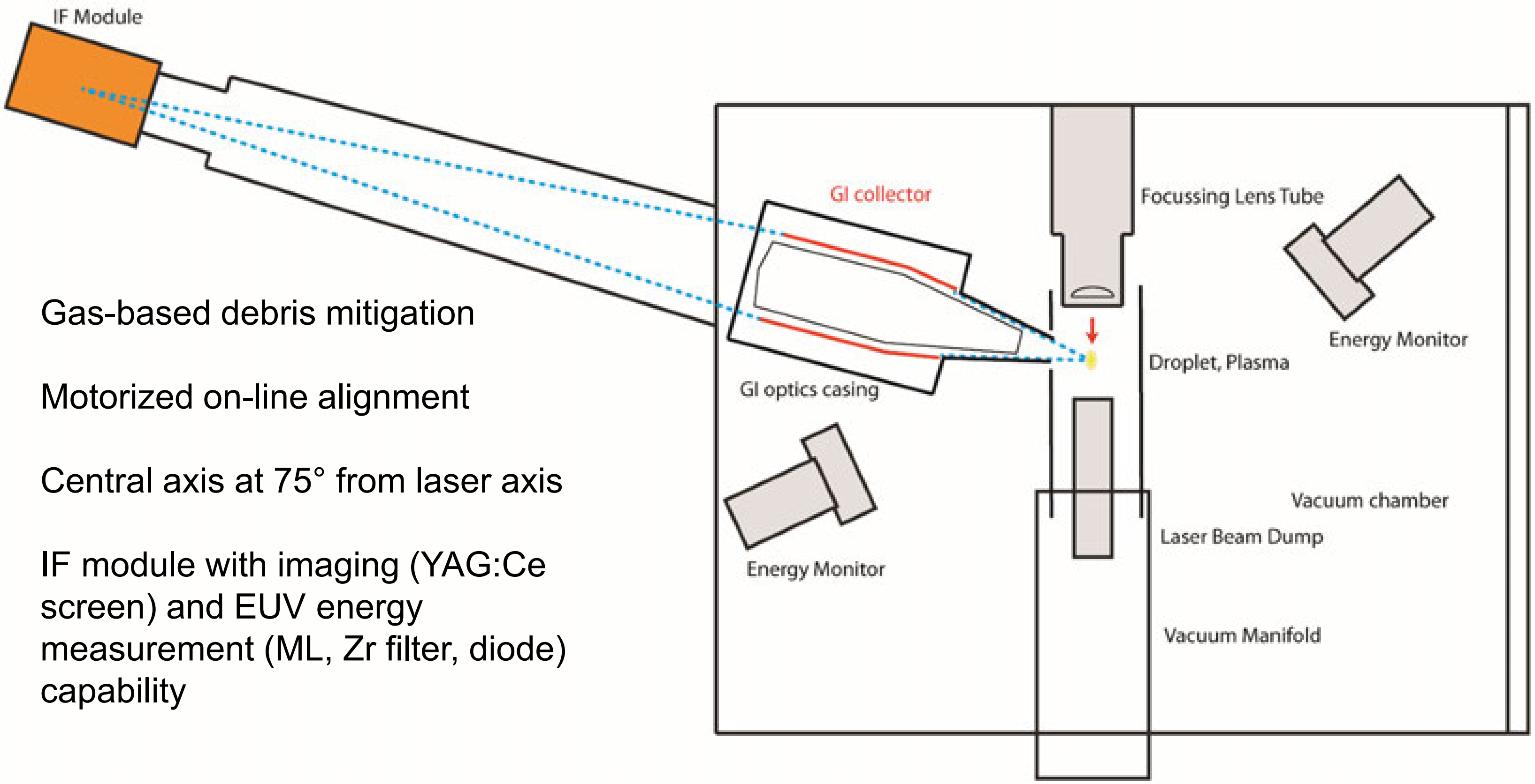


- Sn^+ expands approximately isotropically, and Sn^{2+} expansion is peaked towards the incoming laser radiation (same trend as for ion kinetic energies).

DM LAYER 2

Source Collector Module

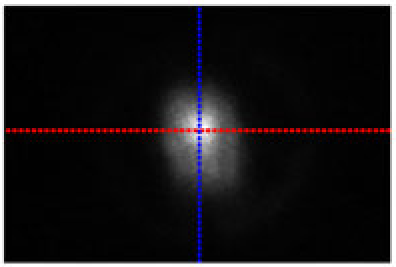
- Grazing Incidence (GI) collector for diagnostics and imaging

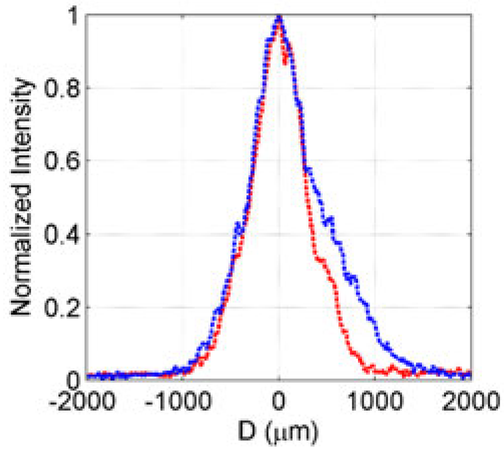


- Gas-based debris mitigation
- Motorized on-line alignment
- Central axis at 75° from laser axis
- IF module with imaging (YAG:Ce screen) and EUV energy measurement (ML, Zr filter, diode) capability

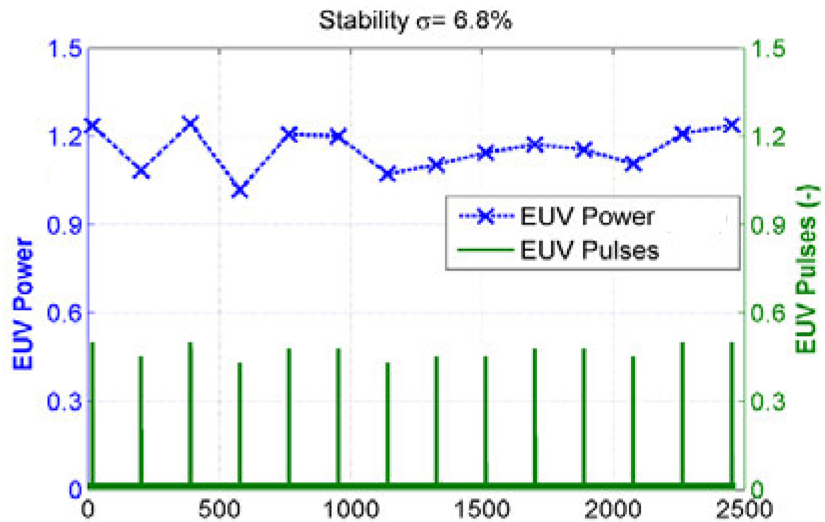
Source Collector Module – Imaging at IF

- Imaging for monitoring of alignment, collector reflectivity drop and focal spot uniformity





Beam uniformity close to IF (FWHM 500 μm)



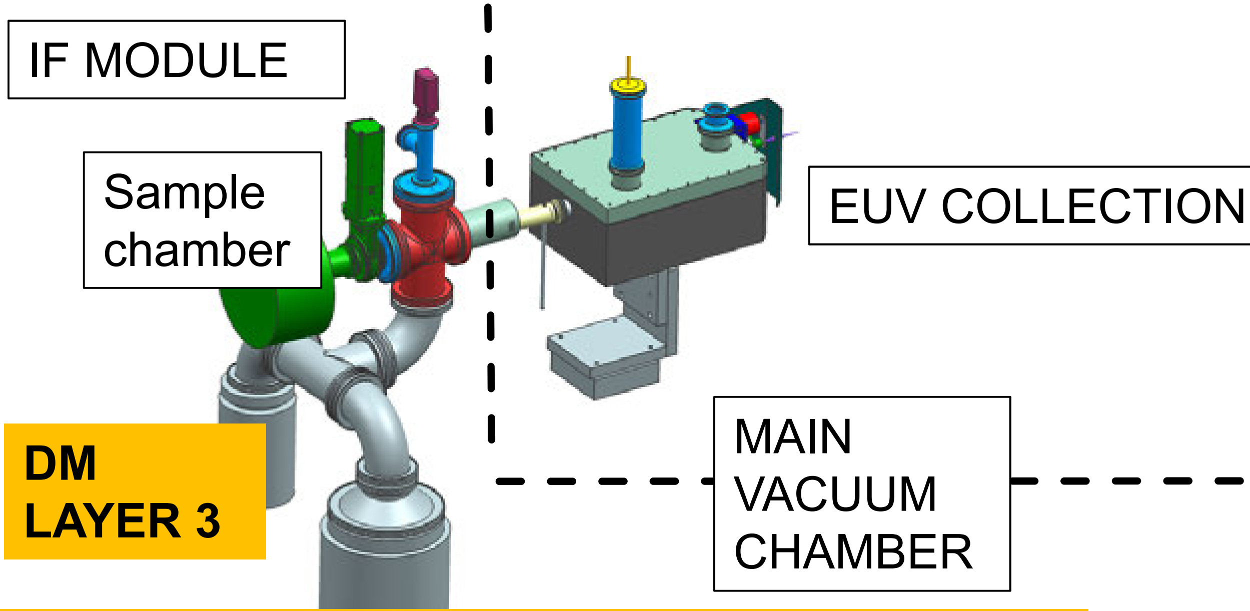
Collected EUV emission on screen

- EUV power measured by photodiode at IF after reflection from ML
- Pulse-to-pulse stability of EUV energy of 6.8% (σ).
- Current setup allows studies of mitigation gas pressure with significant variations in EUV energy at IF

Validated Cleanliness of Tin LPP Source after IF

- Positive assessment of IF cleanliness after 100's hours of operating time.
- Detailed quantification of IF cleanliness for 24 hours source operation. Inspection before / after exposure revealed no relevant contamination.

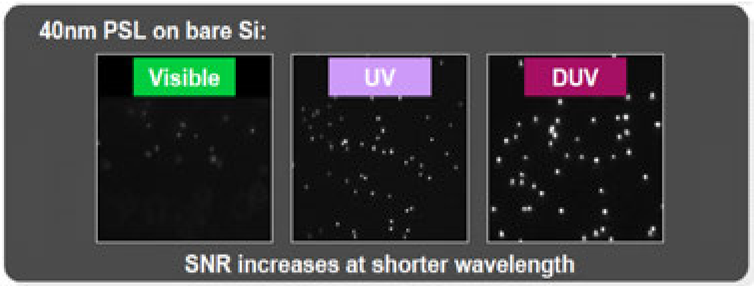
- **EUV Light Extraction Assembly** – Single or *Double bounce mirror assembly with debris mitigated IF module*



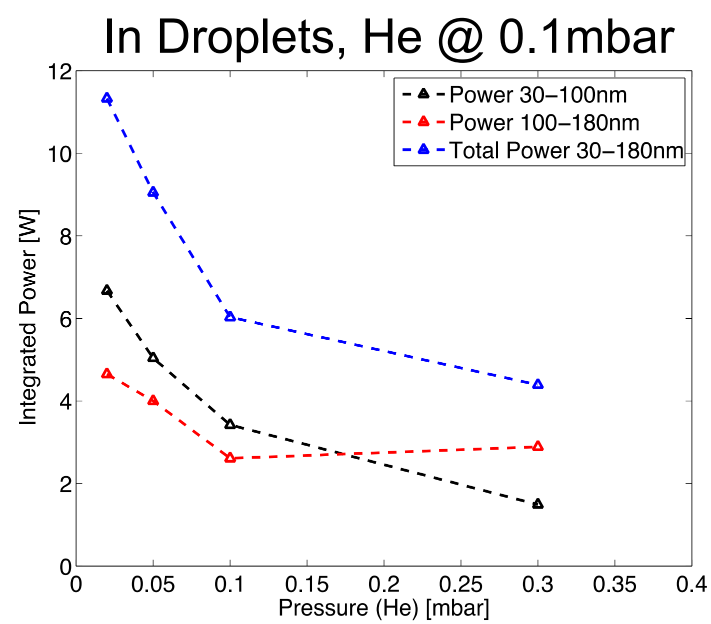
LPP Source Meets EIDEC Requirements for Blank Mask Inspection Cleanliness after IF

Plasma Emission in VUV Range for Inspection Applications

- Fundamental for wide range of processes (overlay measurements, critical dimensions (CD) control, patterned and un-patterned wafers, masks, defects review).
- LPP as key technology was previously developed and de-risked for application in EUV. Potential DUV source for sub-20nm defect sensitivity.

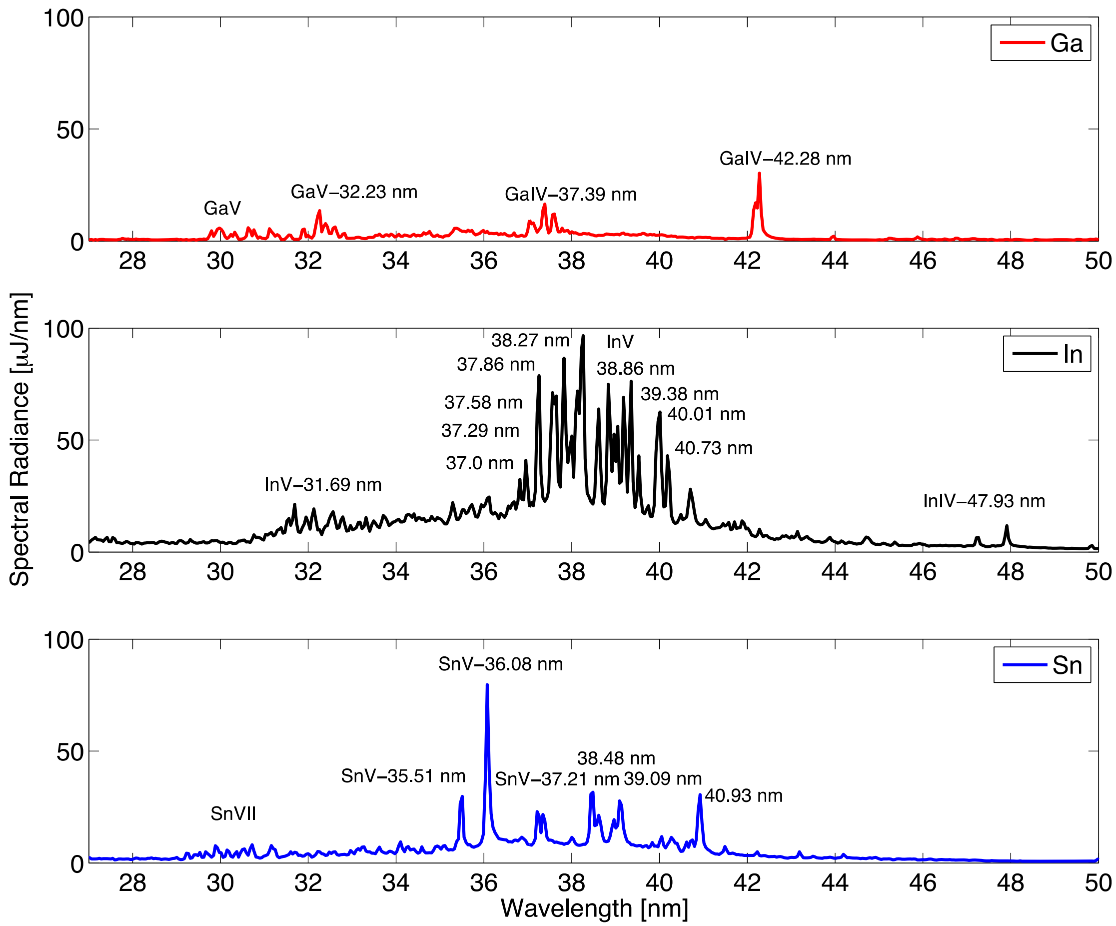


Staud, 2011, Applied Materials



- Calibrated spectral energy emission experimentally measured for the first time on Sn, as well as In and Ga targets between 30 and 160 nm with 0.1 nm spectral resolution
- Tuneable emission (broadband and line emission) possible by tuning the fuel, the ambient gas type

Ga, In and Sn Emissions in the Spectral Range from 30 to 50 nm



- Charge states from 3+ to 6+ observed from 30 to 50 nm
- Indium has higher spectral radiance in He with respect to Sn and Ga

Integrated Power (Watt)

Range (nm)	Ga	In	Sn
30-50	0.27	1.70	0.69
117-137	0.94	1.66	1.34
30-163	2.38	5.8	3.7

- Source power in the range of watts for sub 160 nm

Summary and Conclusions

- Engineering tool (ALPS II) operated as clean EUV source for actinic inspection over hundreds of hours, with validated cleanliness after IF.
- First time reported ICCD imaging of expanding EUV droplet-based LPP in visible and EUV range. Validation of source size measurements.
- Absolute tin droplet-based LPP OOB measurements using calibrated emission spectra.
- 3 layer debris mitigation strategy including plasma site, collector and IF. Grazing and normal incidence collectors integrated in source.
- High source power (W's) achievable in the sub 160 nm emission range.
- On track for long-term testing in industrial environment and commercialization through Adlyte.

Acknowledgments

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